A 10-ZONE THERMAL MANIKIN FOR EVALUATING PERSONNEL PROTECTIVE GARMENTS IN COLD AIR AND WATER IMMERSION ENVIRONMENTS

NAVY CLOTHING AND TEXTILE RESEARCH FACILITY

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A thermal manikin with the dimensions and weight of a fiftieth percentile standing man simulates metabolic heat and will be used for evaluating the thermal protection capability of clothing and diving suits in cold air and/or water environments. The manikin has 10 independently heated and controlled sections made from aluminum castings. Power for each section is controlled by the temperature level of the torso and by temperature differences between adjacent sections. The manikin is water tight at a depth of 3m without internal

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pressurization. A pressure equalization system permits evaluation of protective clothing in water environments equivalent to submersion in 300 m of sea water. An automatic control and data acquisition system computes individual temperatures from thermistor sensors, average section temperatures, section and total power, and both section and total insulation (in units of clo) of the garment being tested. (U)

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A 10-ZONE THERMAL MANIKIN FOR EVALUATING PERSONNEL PROTECTIVE GARMENTS IN COLD AIR AND WATER IMMERSION ENVIRONMENTS

INTRODUCTION

Where protective garments are designed to be worn in extreme temperature conditions, there is often a requirement to evaluate their thermal insulation characteristics. Traditionally, these evaluations have been done with volunteer human subjects. There are, however, a number of limitations for this type of testing. First, the risks to the human subjects exposed to extreme environmental conditions can be high or even unknown. Second, the process of obtaining the required approval to conduct clothing studies with human subjects can be lengthy and involved. Third, the cautions required in designing tests involving human subjects can compromise the testing conditions from those considered optimal. For a number years, "Copper Man" thermal manikins have been used by the US Army Natick Research Laboratories and other organizations for evaluating clothing in cold environments (1, 2). These wholebody calorimeters provide much useful thermal data on overall performance of clothing and other thermal protective garments. One manikin was designed for measuring heat losses from individual zones of the body (3). There was no multisection manikin designed for use in wet environments.

The Navy Clothing and Textile Research Facility (NCTRF) is engaged in programs to develop and evaluate clothing and protective garments for Navy personnel for use in both air and water immersion environments. Specifications were developed by the Navy for an advanced thermal manikin that is capable of simulating metabolic heat produced in man and able to maintain selectable constant temperature within each of 10 sections (head, torso, and right and left legs, feet, arms and hands). This paper describes the design, fabrication and testing of such a manikin and the accompanying control, sensing, and data acquisition system.

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(1) Fitzgerald, J.E., "A Study of the Copper Man Phase I, Physical Characteristics Thermometry; Air Clo Evaluations," Aug. 1946, Quartermaster Corps Climatic Research Laboratory, Lawrence, MA.

(2) Wattenbarger, J.F., and Breckenridge, J.R., "Dry Suit Insulation Characteristics Under Hyperbaric Conditions," Hyperbaric Diving Systems and Thermal Protection Session of the ASME Winter Annual Meeting, Ocean Engineering Division, Vol. 6, 1978, p.101.

(3) Gabron F., and McCullough J., "Thermal Manikin," NASA CR-644, Nov. 1965, Arthur D. Little, Inc., Cambridge, MA.

THERMAL MANIKIN

General Description

The manikin, shown in Figure 1, is made from aluminum castings approximately 12mm thick to form 10 thermally isolated sections. The exterior dimensions and weight correspond approximately to those of a fiftieth percentile adult male in a normal standing position. The arms articulate in one plane by rotating at a shoulder joint to facilitate dressing the manikin. The arms and legs are removable from the torso section for ease of transportation. Access to the inside of the manikin for assembly and maintenance is through a water-tight circular port located in the small of the back. Construction and repair access ports, as shown by the dotted areas in Figure 2, have been designed into the arm and leg sections to allow heaters, sensors, and wiring to be installed. The head, hands, and feet are also removable for major repairs.

The manikin was designed for constant metabolic heat loss per unit of surface area as summarized in Table I. Low thermal conductivity epoxy-fiberglass spacers were used as structural elements between adjacent sections. These spacers limit the heat transfer between sections to less than 1 percent of the normal heat flux per unit area leaving the surface of the manikin, for a 0.5°C temperature difference.

Aluminum was used for construction because of its high thermal conductivity and ease of fabrication by sand casting. The high thermal conductivity of the aluminum allows the use of a small number of surface heaters at convenient locations on the inside of the individual components. A thermal analysis revealed that, for maximum heat flux conditions from the surface, the temperature gradients between adjacent heaters will be less than 1°C for maximum spacing conditions.

TABLE I. APPROXIMATE AREAS AND POWER

No.	Zone	Surface Area (cm^2)	Maximum Power (Watts)
1	Head	1,360	84
2	Torso	8,330	516
3	R. Arm	1,260	78
4	L. Arm	1,260	78
5	R. Hand	580	36
6	L. Hand	580	36
7	R. Leg	2,130	132
8	L. Leg	2,130	132
9	R. Foot	870	54
10	L. Foot	870	54
		19,370	1,200

FIGURE 1 NAVY 10-ZONE THERMAL MANIKIN

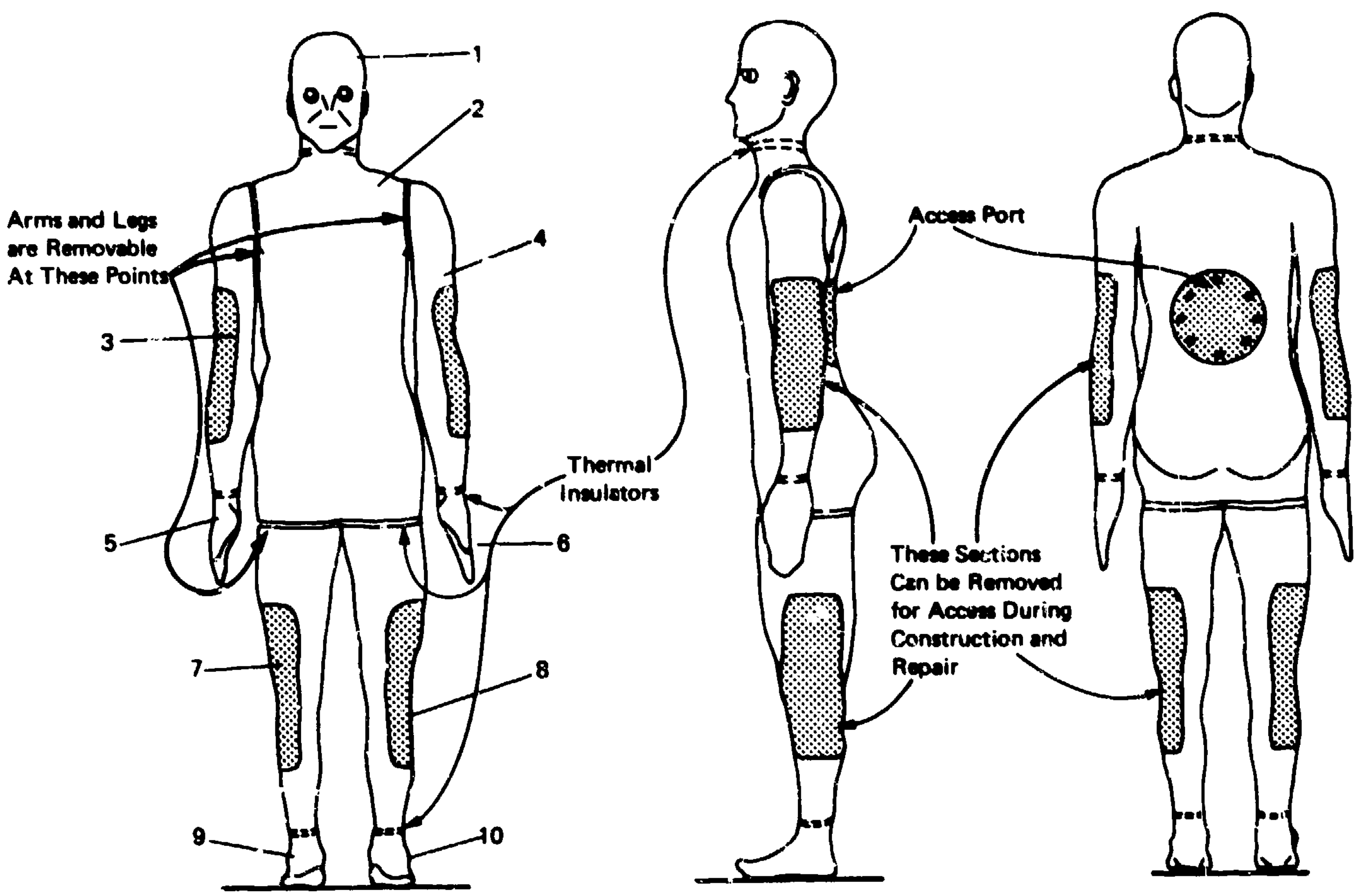

FIGURE 2 CONSTRUCTION AND ACCESS PORTS FOR MANIKIN

Shape Dimensions and Dressing Studies

Early in the program a store manikin was obtained that closely matched the dimensions required. With a large selection of clothing, including a hard hat diving suit, wet suits, and other Navy foul-weather gear, dressing studies were performed to determine if the manikin, as configured, could be dressed. Some difficulty was experienced in dressing the manikin with the Navy Mark V hard hat diving suit. By raising the manikin arms to the overhead position, we could slip the neck ring for the hard hat over the manikin's head.

Patterns and Castings For Manikin

The dressing manikin external dimensions were adjusted with automotive body putty until the critical dimensions for a fiftieth percentile man were achieved. A plaster-of-paris negative mold was made from the modified dressing manikin and, in turn, a pattern manikin was made from polyester resin and fiberglass. The pattern manikin was sawed into discrete sections (head, torso, arms, legs, hands and feet). The hands were discarded and replaced with ones developed from plaster-of-paris molds of actual hands. Each body component was split along a parting line and each half was built up on the inside with modeling clay to an average thickness of approximately 12mm (0.5 in.). Surfaces were developed on the inside of these patterns for receiving the strip heaters that provide the metabolic heat. The hands and feet were cast as solid components. The remaining body pieces were cast as individual halves and then welded together along prepared seams. Machine joints were welded into the castings for attachment of the legs and arms.

Access to the internal components is through a porthole that is machined into the small of the back. The access port, which uses an O-ring seal, is fastened to the manikin with multiple flush fasteners.

Metabolic Heat Simulation and Temperature Sensing

The total power input to the manikin is 1200 watts. Each zone receives an amount of power that is proportional to a fraction of the total area. Heat is supplied by strip heaters made from heating wires embedded in silicone rubber. These heaters are cemented to the inside surface of the manikin and are connected to leads that terminate in a multi-pin waterproof connector mounted in an eye socket.

Temperatures are sensed at 53 locations within the manikin. The temperature sensors are space-qualified thermistors that are individually tested and have an interchangeability of $\pm$ 0.1°C. The thermister distribution is summarized in Table II. Leads from the thermistors are terminated in a multi-pin waterproof connector located in the other eye socket.

Internal power and thermistor connectors are used to make the arms and legs removable. Connection is made between the manikin and the operating console with two separate cables. One cable is devoted to the temperature measurements and the other cable carries the power to the manikin internal heaters. Heaters and thermistor temperature sensors are installed in the ends of the cables that attach to the manikin. These heaters are controlled by individual power supplies and serve as guards to minimize the heat loss from the head section out through the cables. The cables are designed to withstand a pressure of 6900kPa (1,000 psi). A separate thermistor is used to measure the ambient temperature.

TABLE 11. DISTRIBUTION OF TEMPERATURE SENSORS

Section	Number of Thermistors
Head	6
Torso	15
L. Arm	5
R. Arm	5
L. Hand	3
R. Hand	3
L. Leg	5
R. Leg	5
L. Foot	3
R. Foot	3
Power Cable	1
Thermistor Cable	1
Ambient Temperature Sensor	1
TOTAL	56

Pressure Equalization System

A pressure equalization system is used to maintain a slight positive pressure 34.5kPa (5.0 psig) in the manikin during water submersion tests.

CONTROL, SENSING, AND DATA ACQUISITION SYSTEM (CSDA)

General Description

The CSDA system shown schematically in Figure 3 consists of:

- A Digital Equipment Corporation MINC laboratory computer system complete with three D/A boards for a total of 12 digital-to-analog outputs, a CRT console, keyboard, printer and dual floppy disk. The computer consists of a PDP 11 micro computer with extended arithmetic and floating point hardware, 64 Kb MOS memory and standard basic software package,

- A Kiethley model 703/7031 100 channel multiplexer interconnected with a Kiethley model 7031 IEEE 488 interface,

- A Data Precision model 3400 digital multimeter interconnected with a Data Precision model 3410 IEEE 488 interface,

- 12 Kepco programmable power supplies (one for each zone and for each cable) for control of heaters,

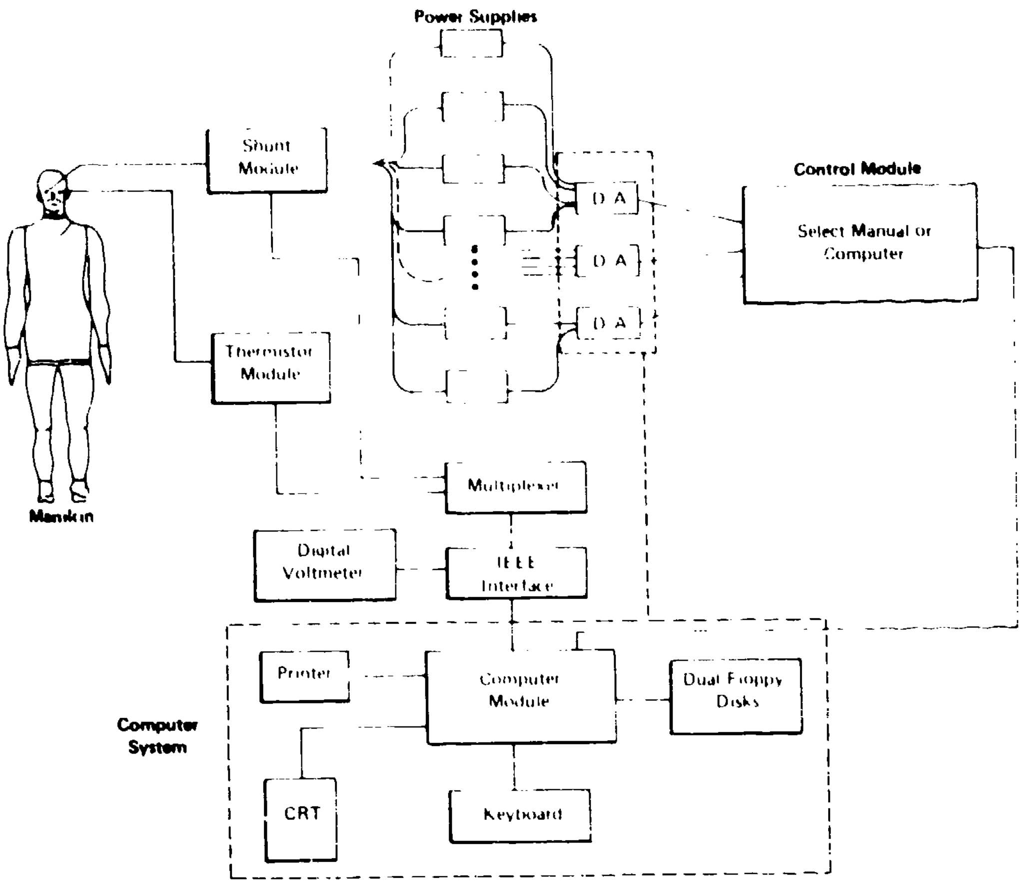

FIGURE 3 SCHEMATIC FOR CONTROL SENSING AND DATA ACQUISITION SYSTEM

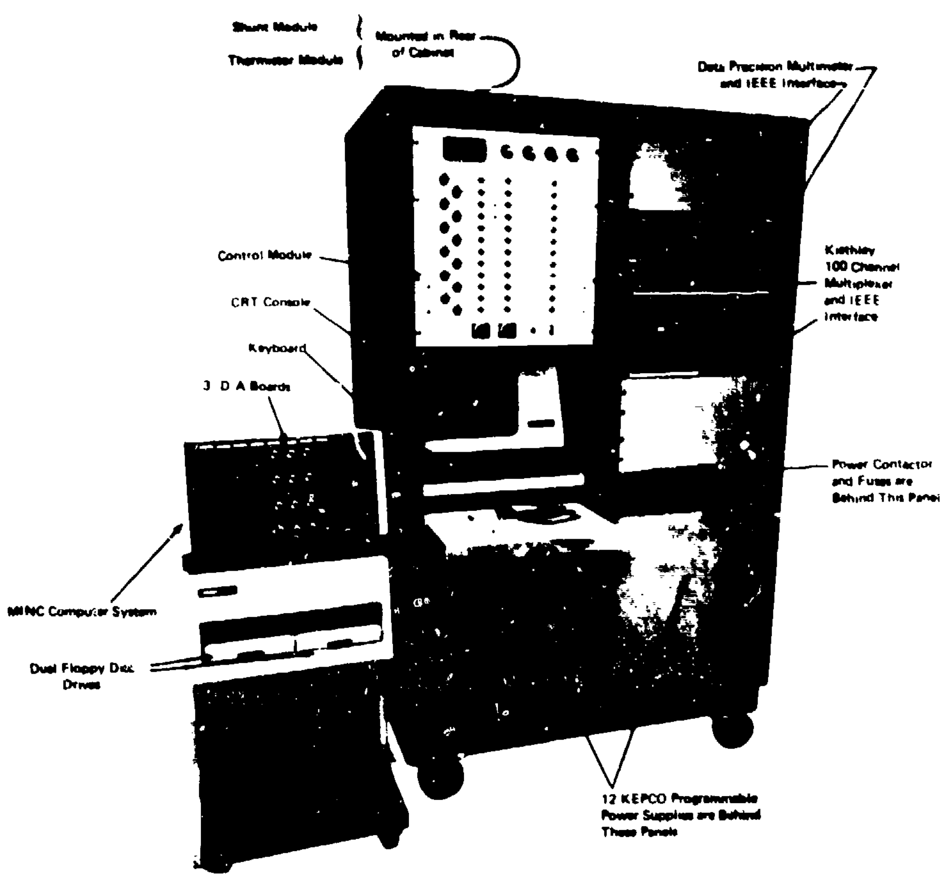

FIGURE 4 CONTROL, SENSING AND DATA ACQUISITION SYSTEM (CSDA)

- A shunt module where the power to each major zone is monitored,

- A thermistor module where the resistance of each of the 56 thermistors is measured, and

- A control module where manual or automatic control for each zone can be selected.

Figure 4 shows all components of the CSDA system except the printer.

All software (programming) is executed using the BASIC language supplied with the MINC system. The software is organized into seven major functions:

- Data collection,

- Temperature calculation,

- Power calculation,

- Control calculation and output,

- Display update,

- Operator request, and

- Data Logging.

The functions of the data acquisition and control systems are to: control the temperature of the manikin to an operator-entered setpoint; measure, calculate and log the thermal insulation value of each region of the manikin expressed in terms of clo values; and monitor and alarm equipment failure.

Data Acquisition

All thermistor resistances are measured directly with the digital multimeter and converted to temperature by the functional relationship.

$$T = 1.0 / [A + B \ln R + C (\ln R)^3]$$

where A, B and C are calibration constants for each thermistor

R = thermistor resistance

Upon completion of the temperature calculations, the system computes the average temperature for each region, the differential temperature in each region, and the average differential temperature at each regional boundary, and stores these values for display and subsequent calculation usage. The control logic sets the torso temperature and adjusts the adjacent zone temperature (head, arms and legs) until the temperature differential at each zone boundary is less than $\pm$ 0.25°C. In similar manner, the power applied to each hand and each foot is adjusted until the differential temperature at the boundary is $\pm$ 0.25°C. This cascading of the temperature control assures that minimum heat is transferred between adjacent zones and that the power measured in any given zone is for heat that is transferred out through the clothing.

The procedure for power calculations requires measuring the voltage applied to the heaters in each zone and the voltage across the shunt assigned to each zone. Power to each zone is calculated from

$$P = V_1 V_2 / R_s$$

where V_1 = voltage across the circuit

V_2 = voltage across the shunt

R_s = shunt resistance

During start-up, the computer program calls for raising all zone temperatures to the torso set-point temperature. As each zone approaches the torso temperature, control is transferred to the cascade mode of operation where adjacent sections are automatically controlled until the temperature difference at boundaries is less than $\pm$ 0.25°C. The computer program automatically calls for an increase or decrease in zone temperature depending upon whether the adjacent temperatures are below or above the torso temperature.

Provision is made for monitoring of all the variables associated with the control process and displaying these variables both on the CRT and on the printer.

Thermal Insulation of Garments

The thermal protection copability of clothing assemblies is calculated directly from the temperature differences between the manikin and the ambient, and the power supplied to the manikin to maintain the desired manikin temperature. The thermal protection is calculated for each of the 10 zones and for the manikin as a whole. The protection capability is expressed in terms of clo (4). Clo is a unit of insulation and is the amount of insulation necessary to maintain comfort at a mean skin temperature of 33°C (92°F) in a room at 21°C (70°F) with air movement not over 3.1 m/min (10ft/min), humidity not over 50%, with a metabolism of 58.1 w/m^2 (50 kcal/m^2 hr). In physical terms clo is the amount of insulation that will allow the passage of 1.0 kilogram calorie of energy per square meter per hour with a temperature gradient of 0.18°C between the two surfaces.

$$1.0 \text{ clo} = \frac{0.18°\text{C m}^2 \text{ hr}}{\text{kcal}}$$

(Ordinary men's business clothing has an insulation value of about 1.0 clo).

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(4) Gagge, A.P., Burton, A.C., and Bazett, H. C., "A Practical System of Units for the Description of Heat Exchange of Man with His Environment," Science 94: 428, 1941.

PERFORMANCE TESTS

Before delivery of the manikin, the following tests will be conducted:

Temperature Uniformity

Temperature uniformity tests will be made with all of the sections set at an average temperature of 37°C and with the manikin nude in a 10°C air temperature. These tests will be conducted in a controlled environment test chamber at the Navy Clothing and Textile Research Facility.

Ten-Foot Water Test

Proper operation of all sensors, heaters, connectors, and control systems will be checked out with the manikin immersed in 3m (10 feet) of water. These tests will be carried out in a swimming pool. The nude manikin will be ballasted with sufficient weight so that it will sink to the bottom of the pool. Initially, the manikin will be pressurized to determine if there are leaks. If there are no leaks, the pressure will be vented to atmospheric and all circuits will be checked.

One-Thousand-Foot Water Submersion Test

The manikin will be tested at the Naval Coastal Systems Center, Panama City, Florida, in a 122 cm (48 inch) diameter, 223 cm (88 inch) long test chamber. In these tests, the manikin will be placed horizontally in an open water-tight box with sufficient water to cover the manikin. The box, water, and manikin will be subjected to 2988kPa (433 psi) pressure dry nitrogen in the test chamber. Provisions will be made for maintaining a positive pressure of 34.5 kPa (5.0 psi) dry nitrogen within the manikin. The water in the test box will be maintained at approximately 4°C by an external refrigertion coil. Proper control and functioning of the manikin will be demonstrated.